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Models of solar radiation with hours of bright sunshine: A review

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ABSTRACT

In the design and study of solar energy, information on solar radiation and its components at a given location is very essential. Solar radiation data are required by solar engineers, architects, agriculturists and hydrologists for many applications such as solar heating, cooking, drying and interior illumination of buildings. For this purpose, in the past, several empirical correlations have been developed in order to estimate the solar radiation around the world. The main objective of this study is to review the global solar radiation models available in the literature. There are several formulate which relate global radiation to other climatic parameters such as sunshine hours, relative humidity and maximum temperature. The most commonly used parameter for estimating global solar radiation is sunshine duration. Sunshine duration can be easily and reliably measured and data are widely available.

Contents

1. Introduction

Information of local solar radiation is essential for many applications, including architectural design, solar energy systems and particularly for design. Unfortunately, for many developing countries, solar radiation measurements are not easily available due to the cost and maintenance and calibration requirements of the measuring equipment. Therefore, it is important to elaborate methods to estimate the solar radiation based on readily available meteorological data.

Several empirical models have been developed to calculate global solar radiation using various climatic parameters. These parameters include extraterrestrial radiation, sunshine hours, mean temperature, maximum temperature, soil temperature, relative humidity, number of rainy days, altitude, latitude, total precipitation, cloudiness and evaporation. The most commonly used parameter for estimating global solar radiation is sunshine duration. Sunshine duration can be easily and reliably measured and data are widely available.

The design of a solar energy conversion system needs exact knowledge regarding the availability of global solar radiation. Sunshine hours are measured at many locations around the world, while global radiation is measured at selected locations only. In order to overcome this defectiveness, scientists have developed many empirical equations. Most of the sunshine based this equations built to estimate the monthly average daily global solar radiation are of the modified Angström-type equation.

Determination of the solar energy capacity of a region requires that extensive radiation measurements of high quality be made at a large number of stations covering the major climatic zones of the region. In this regard, recently, several empirical formulas using various parameters have been given to estimate the solar radiation around the world. Estimations of the monthly average daily global solar radiation for a large number of locations are presented in various works [1–63].

The main objective of this study is to review the global solar radiation models available in the literature, including the study

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Nomenclature

a, b	regression coefficients
H	monthly average daily global radiation on horizontal surface ($MJ\,m^{-2}\,d^{-1}$)
H_o	monthly average daily extraterrestrial radiation ($MJ\,m^{-2}\,d^{-1}$)
I_{sc}	solar constant ($W\,m^{-2}$)
S	monthly average daily hours of bright sunshine (h)
S_o	monthly average day length (h)
Z	altitude of site (km)
δ	solar declination (°)
φ	latitude of the location (°)
ω_s	sunset hour angle (°)

carried out on the estimation of the monthly average daily global solar radiation on horizontal surfaces.

2. Models used

The simple model used to estimate monthly average daily global solar radiation on horizontal surface is the modified form of the Angström-type equation. The original Angström-type regression equation related monthly average daily radiation to clear day radiation at the location in question and average fraction of possible sunshine hours [1]. Page [2] and others have modified the method to base it on extra-terrestrial radiation on horizontal surface rather than on clear day radiation [64]:

$$\frac{H}{H_o} = a + b\left(\frac{S}{S_o}\right) \quad (1)$$

where H is the monthly average daily global radiation, H_o is the monthly average daily extraterrestrial radiation, S is the monthly average daily hours of bright sunshine (h), S_o is the monthly average day length (h), and a and b are empirical coefficients.

The monthly average daily extraterrestrial radiation on a horizontal surface (H_o) can be computed from the following equation [64]:

$$H_o = \frac{24}{\pi} I_{sc}\left(1 + 0.033\cos\frac{360D}{365}\right) \times \left(\cos\varphi\cos\delta\sin\omega_s + \frac{2\pi\omega_s}{360}\sin\varphi\sin\delta\right) \quad (2)$$

where I_{sc} is the solar constant (=1353 $W\,m^{-2}$), φ the latitude of the site, δ the solar declination, ω_s the mean sunrise hour angle for the given month and D the number of days of the year starting from first January. The solar declination (δ) and the mean sunrise hour angle (ω_s) can be calculated by Eqs. (3) and (4), respectively [64].

$$\delta = 23.45\sin\left[\frac{360(D+284)}{365}\right] \quad (3)$$

$$\omega_s = \cos^{-1}[-\tan(\delta)\tan(\varphi)] \quad (4)$$

For a given month, the maximum possible sunshine duration (monthly average day length, S_o) can be computed by using the following equation [64]:

$$S_o = \frac{2}{15}\omega_s \quad (5)$$

The regression models that have been proposed in the literature are given below.

Model 1: Glover and McCulloch proposed the following equation which depends on φ and is valid for $\varphi < 60^\circ$ [4]:

$$\frac{H}{H_o} = 0.29\cos(\varphi) + 0.52\left(\frac{S}{S_o}\right) \quad (6)$$

Model 2: Page has given the coefficients of the modified Angström-type model, which is believed to be applicable anywhere in the world, as the following [2]:

$$\frac{H}{H_o} = 0.23 + 0.48\left(\frac{S}{S_o}\right) \quad (7)$$

Model 3: Rietveld examined several published values of the a and b from following equations, respectively [5]:

$$a = 0.10 + 0.24\left(\frac{S}{S_o}\right) \quad (8a)$$

$$b = 0.38 + 0.08\left(\frac{S}{S_o}\right) \quad (8b)$$

Model 4: Iqbal used dada obtained from three locations in Canada to propose the correlations [6]:

$$\frac{H_d}{H} = 0.791 - 0.635\left(\frac{S}{S_o}\right) \quad (9a)$$

$$\frac{H_d}{H_o} = 0.163 + 0.478\left(\frac{S}{S_o}\right) - 0.655\left(\frac{S}{S_o}\right)^2 \quad (9b)$$

Model 5: Gariepy has reported that the empirical coefficient a and b are dependent on mean air temperature (T) and the amount of precipitation (P) [7]:

$$a = 0.3791 - 0.0041(T) - 0.0176(P) \quad (10a)$$

$$b = 0.4810 + 0.0043(T) + 0.0097(P) \quad (10b)$$

Model 6: Kilic and Ozturk [8] have determined that the coefficients a and b are a function of the solar declination (δ) in addition to both φ and Z, as given by the equations [11]:

$$a = 0.103 + 0.017Z + 0.198\cos(\varphi - \delta) \quad (11a)$$

$$b = 0.533 - 0.165\cos(\varphi - \delta) \quad (11b)$$

Model 7: Lewis obtained the following linear regression equation to estimate the daily diffuse radiation for three stations in Zimbabwe [9]:

$$\frac{H_d}{H} = 0.754 - 0.654\left(\frac{S}{S_o}\right) \quad (12)$$

Model 8: Kholagi et al. derived the following equations from the data measured at three different stations in Yemen [10]:

$$\frac{H}{H_o} = 0.191 + 0.571\left(\frac{S}{S_o}\right) \quad (13a)$$

$$\frac{H}{H_o} = 0.297 + 0.432\left(\frac{S}{S_o}\right) \quad (13b)$$

$$\frac{H}{H_o} = 0.262 + 0.454\left(\frac{S}{S_o}\right) \quad (13c)$$

Model 9: Dogniaux and Lemoine have also proposed following equation, where the regression coefficients a and b seem to be as a function of φ in average and on the monthly base in these equations, respectively [11].

$$a = 0.37022 - 0.00313(\varphi) \quad (14a)$$

$$b = 0.32029 + 0.00506(\varphi) \quad (14b)$$

$$\frac{H}{H_o} = (0.34507 - 0.00301\varphi) + (0.34572 + 0.00495\varphi)\left(\frac{S}{S_o}\right) \quad \text{for January} \tag{14c}$$

$$\frac{H}{H_o} = (0.33459 - 0.00255\varphi) + (0.35533 + 0.00457\varphi)\left(\frac{S}{S_o}\right) \quad \text{for February} \tag{14d}$$

$$\frac{H}{H_o} = (0.36690 - 0.00303\varphi) + (0.36377 + 0.00466\varphi)\left(\frac{S}{S_o}\right) \quad \text{for March} \tag{14e}$$

$$\frac{H}{H_o} = (0.38557 - 0.00334\varphi) + (0.35802 + 0.00456\varphi)\left(\frac{S}{S_o}\right) \quad \text{for April} \tag{14f}$$

$$\frac{H}{H_o} = (0.35057 - 0.00245\varphi) + (0.33550 + 0.00485\varphi)\left(\frac{S}{S_o}\right) \quad \text{for May} \tag{14g}$$

$$\frac{H}{H_o} = (0.39890 - 0.00327\varphi) + (0.27292 + 0.00578\varphi)\left(\frac{S}{S_o}\right) \quad \text{for June} \tag{14h}$$

$$\frac{H}{H_o} = (0.41234 - 0.00369\varphi) + (0.27004 + 0.00568\varphi)\left(\frac{S}{S_o}\right) \quad \text{for July} \tag{14i}$$

$$\frac{H}{H_o} = (0.36243 - 0.00269\varphi) + (0.33162 + 0.00412\varphi)\left(\frac{S}{S_o}\right) \quad \text{for August} \tag{14j}$$

$$\frac{H}{H_o} = (0.39467 - 0.00338\varphi) + (0.27125 + 0.00564\varphi)\left(\frac{S}{S_o}\right) \quad \text{for September} \tag{14k}$$

$$\frac{H}{H_o} = (0.36213 - 0.00317\varphi) + (0.31790 + 0.00504\varphi)\left(\frac{S}{S_o}\right) \quad \text{for October} \tag{14l}$$

$$\frac{H}{H_o} = (0.36680 - 0.00350\varphi) + (0.31467 + 0.00523\varphi)\left(\frac{S}{S_o}\right) \quad \text{for November} \tag{14m}$$

$$\frac{H}{H_o} = (0.36262 - 0.00350\varphi) + (0.30675 + 0.00559\varphi)\left(\frac{S}{S_o}\right) \quad \text{for December} \tag{14n}$$

Model 10: Benson et al. proposed two different equations into two intervals of a year depending on the climatic parameters [12].

$$\frac{H}{H_o} = 0.18 + 0.60\left(\frac{S}{S_o}\right) \quad \text{for January–March and October–December} \tag{15a}$$

$$\frac{H}{H_o} = 0.24 + 0.53\left(\frac{S}{S_o}\right) \quad \text{for April–September} \tag{15b}$$

Model 11: Ogelman et al. have correlated (H/H_o) with (S/S_o) in the form of a second order polynomial equation [13]:

$$\frac{H}{H_o} = 0.195 + 0.676\left(\frac{S}{S_o}\right) - 0.142\left(\frac{S}{S_o}\right)^2 \tag{16}$$

Model 12: Ibrahim obtained the following equations to predict the monthly main daily diffuse radiation in Cairo, Egypt [14]:

$$\frac{H_d}{H} = 0.79 - 0.59\left(\frac{S}{S_o}\right) \tag{17a}$$

$$\frac{H_d}{H_o} = 0.252 - 0.0001\left(\frac{S}{S_o}\right) - 0.083\left(\frac{S}{S_o}\right)^2 \tag{17b}$$

Model 13: Bahel et al. suggested the following relationship [15]:

$$\frac{H}{H_o} = 0.175 + 0.552\left(\frac{S}{S_o}\right) \tag{18}$$

Model 14: Zabara proposed monthly a and b values of the modified Angström model as a third order function of maximum possible sunshine duration (S) and day length (S_o) [16].

$$a = 0.395 - 1.247\left(\frac{S}{S_o}\right) + 2.680\left(\frac{S}{S_o}\right)^2 - 1.674\left(\frac{S}{S_o}\right)^3 \tag{19a}$$

$$b = 0.395 + 1.384\left(\frac{S}{S_o}\right) - 3.249\left(\frac{S}{S_o}\right)^2 + 2.055\left(\frac{S}{S_o}\right)^3 \tag{19b}$$

Model 15: Jain fitted the Angström equation using the least-square method to the monthly average daily global radiation and the sunshine duration data of 31 Italian locations. The equation using the mean values of these locations is given as follow [17]:

$$\frac{H}{H_o} = 0.177 + 0.692\left(\frac{S}{S_o}\right) \tag{20}$$

Model 16: Alsaad derived the Angström-type equation to estimate the monthly average daily global radiation for Amman, Jordan [18]:

$$\frac{H}{H_o} = 0.174 + 0.615\left(\frac{S}{S_o}\right) \tag{21}$$

Model 17: Bahel also developed a worldwide correlation based on bright sunshine hours and global radiation data of 48 stations around the world, with varied meteorological conditions and a wide distribution of geographic locations [19]:

$$\frac{H}{H_o} = 0.16 + 0.87\left(\frac{S}{S_o}\right) - 0.61\left(\frac{S}{S_o}\right)^2 + 0.34\left(\frac{S}{S_o}\right)^3 \tag{22}$$

Model 18: Gopinathan has suggested that the coefficients a and b are a function of (S/S_o) and the altitude of the site (Z), as given by the equations following equation [20]:

$$a = 0.265 + 0.07Z - 0.135\left(\frac{S}{S_o}\right) \tag{23a}$$

$$b = 0.401 - 0.108Z + 0.325\left(\frac{S}{S_o}\right) \tag{23b}$$

Model 19: Gopinathan has given the following correlations [21]:

$$\frac{H}{H_o} = -0.309 + 0.539\cos(\varphi) - 0.0693Z + 0.290\left(\frac{S}{S_o}\right) + \left(1.527 - 1.027\cos(\varphi) + 0.0926Z - 0.359\left(\frac{S}{S_o}\right)\right)\left(\frac{S}{S_o}\right) \tag{24}$$

where Z is altitude in kilometres.

Model 20: Gopinathan obtained the following equations from the experimental data of three stations in India [22]:

$$\frac{H_d}{H} = 0.931 - 0.814\left(\frac{S}{S_o}\right) \tag{25a}$$

$$\frac{H_d}{H} = 1.194 - 0.838\left(\frac{H}{H_o}\right) - 0.446\left(\frac{S}{S_o}\right) \tag{25b}$$

Model 21: Jain and Jain used following equation to estimate the global radiation over eight Zambian locations [23]:

$$\frac{H}{H_o} = 0.240 + 0.513\left(\frac{S}{S_o}\right) \tag{26}$$

Model 22: Newland suggested following equation which includes a logarithmic term [24].

$$\frac{H}{H_o} = 0.34 + 0.40\left(\frac{S}{S_o}\right) + 0.17\log\left(\frac{S}{S_o}\right) \tag{27}$$

Model 23: Soler has given a modified Angström-type equation for each month as follows [25]:

$$\frac{H}{H_o} = 0.18 + 0.66\left(\frac{S}{S_o}\right) \quad \text{for January} \tag{28a}$$

$$\frac{H}{H_o} = 0.20 + 0.60\left(\frac{S}{S_o}\right) \quad \text{for February} \tag{28b}$$

$$\frac{H}{H_o} = 0.22 + 0.58\left(\frac{S}{S_o}\right) \quad \text{for March} \tag{28c}$$

$$\frac{H}{H_o} = 0.20 + 0.62\left(\frac{S}{S_o}\right) \quad \text{for April} \tag{28d}$$

$$\frac{H}{H_o} = 0.24 + 0.52\left(\frac{S}{S_o}\right) \quad \text{for May} \tag{28e}$$

$$\frac{H}{H_o} = 0.24 + 0.53\left(\frac{S}{S_o}\right) \quad \text{for June} \tag{28f}$$

$$\frac{H}{H_o} = 0.23 + 0.53\left(\frac{S}{S_o}\right) \quad \text{for July} \tag{28g}$$

$$\frac{H}{H_o} = 0.22 + 0.55\left(\frac{S}{S_o}\right) \quad \text{for August} \tag{28h}$$

$$\frac{H}{H_o} = 0.20 + 0.59\left(\frac{S}{S_o}\right) \quad \text{for September} \tag{28i}$$

$$\frac{H}{H_o} = 0.19 + 0.60\left(\frac{S}{S_o}\right) \quad \text{for October} \tag{28j}$$

$$\frac{H}{H_o} = 0.17 + 0.66\left(\frac{S}{S_o}\right) \quad \text{for November} \tag{28k}$$

$$\frac{H}{H_o} = 0.18 + 0.65\left(\frac{S}{S_o}\right) \quad \text{for December} \tag{28l}$$

Also, the regression coefficients of a and b was found for the 100 stations given in Ref. [25] as follows:

$$a = 0.179 + 0.099\left(\frac{S}{S_o}\right) \tag{29m}$$

$$b = 0.1640 + 0.1786\left(\frac{S}{S_o}\right) - 1.0935\left(\frac{S}{S_o}\right)^2 \tag{29n}$$

Model 24: Luhanga and Andringa derived their own model as follow [26]:

$$\frac{H}{H_o} = 0.241 + 0.488\left(\frac{S}{S_o}\right) \tag{30}$$

Model 25: Raja and Twidell provided the following equations using the data from five main observatories in Pakistan and by taking into account the effect of latitude, φ, [27,28].

$$\frac{H}{H_o} = 0.335 + 0.367\left(\frac{S}{S_o}\right) \tag{31a}$$

$$\frac{H}{H_o} = 0.388\ \cos(\varphi) + 0.367\left(\frac{S}{S_o}\right) \tag{31b}$$

Model 26: Akinoglu and Ecevit obtained the correlation below between (H/H_o) and (n/N) in a second order polynomial equation for Turkey [29]:

$$\frac{H}{H_o} = 0.145 + 0.845\left(\frac{S}{S_o}\right) - 0.280\left(\frac{S}{S_o}\right)^2 \tag{32}$$

Model 27: Jain explained results of the following linear regression analysis of measured data for the three locations (Salisbury, Bulawayo and Macerata, Italy), respectively [30]:

$$\frac{H}{H_o} = 0.313 + 0.474\left(\frac{S}{S_o}\right) \tag{33a}$$

$$\frac{H}{H_o} = 0.307 + 0.488\left(\frac{S}{S_o}\right) \tag{33b}$$

$$\frac{H}{H_o} = 0.309 + 0.599\left(\frac{S}{S_o}\right) \tag{33c}$$

Model 28: Samuel expressed the ratio of global to extra-terrestrial radiation as a function of the ratio of sunshine duration [31]:

$$\frac{H}{H_o} = -0.14 + 2.52\left(\frac{S}{S_o}\right) - 3.71\left(\frac{S}{S_o}\right)^2 + 2.24\left(\frac{S}{S_o}\right)^3 \tag{34}$$

Model 29: Tasdemiroglu and Sever came up with the following equations for Turkey in general [32]:

$$\frac{H_d}{H} = 0.622 - 0.350\left(\frac{S}{S_o}\right) \quad \text{for } 0.2 \le \left(\frac{S}{S_o}\right) \le 0.94 \tag{35}$$

Model 30: Tasdemiroglu and Sever also developed a correlation between (H/H_o) and (S/S_o) in a second order polynomial equation for six locations (Ankara, Antalya, Diyarbakir, Gebze, Izmir and Samsun) of Turkey as follow [33]:

$$\frac{H}{H_o} = 0.225 + 0.014\left(\frac{S}{S_o}\right) + 0.001\left(\frac{S}{S_o}\right)^2 \tag{36}$$

Model 31: Louche et al. suggested the model below to estimate global solar radiation [34]:

$$\frac{H}{H_o} = 0.206 + 0.546\left(\frac{S}{S_o}\right) \tag{37}$$

Model 32: Lewis derived the equations including the linear and three-order polynomial relationships between the monthly average values of (H/H_o) and (S/S_o) for locations in the state of Tennessee, U.S.A. as follows [35]:

$$\frac{H}{H_o} = 0.14 + 0.57\left(\frac{S}{S_o}\right) \tag{38a}$$

$$\frac{H}{H_o} = 0.81 - 3.34\left(\frac{S}{S_o}\right) + 7.38\left(\frac{S}{S_o}\right)^2 - 4.51\left(\frac{S}{S_o}\right)^3 \tag{38b}$$

Model 33: Gopinathan and Soler suggested linear equation for locations with latitudes between 60°N and 70°N [36]:

$$\frac{H}{H_o} = 0.1538 + 0.7874\left(\frac{S}{S_o}\right) \tag{39a}$$

$$\frac{H}{H_o} = 0.1961 + 0.7212\left(\frac{S}{S_o}\right) \tag{39b}$$

Model 34: Veeran and Kumar obtained the following linear relation to estimate the monthly average daily global radiation at two tropical locations (Madras and Kodaikanal, India), respectively [37]:

$$\frac{H}{H_o} = 0.34 + 0.32\left(\frac{S}{S_o}\right) \tag{40a}$$

$$\frac{H}{H_o} = 0.27 + 0.65\left(\frac{S}{S_o}\right) \tag{40b}$$

Model 35: Yildiz and Oz, using the measured data gathered from five stations located in different places of Turkey, developed the following equation [38]:

$$\frac{H}{H_o} = 0.2038 + 0.9236\left(\frac{S}{S_o}\right) - 0.3911\left(\frac{S}{S_o}\right)^2 \tag{41}$$

Model 36: Tiris et al. also suggested the following correlations [39]:

$$\frac{H}{H_o} = 0.2262 + 0.418\left(\frac{S}{S_o}\right) \tag{42a}$$

$$\frac{H_d}{H} = 0.4177 + 0.0070\left(\frac{S}{S_o}\right) - 1.9096\left(\frac{S}{S_o}\right)^2 - 1.19\left(\frac{S}{S_o}\right)^3 \tag{42b}$$

$$\frac{H_d}{H} = 0.1426 - 0.119\left(\frac{S}{S_o}\right) \tag{42c}$$

$$\frac{H_b}{H_o} = 0.0851 - 0.298\left(\frac{S}{S_o}\right) \tag{42d}$$

$$\frac{H_b}{H} = 0.4428 - 0.1747\left(\frac{S}{S_o}\right) \tag{42e}$$

Model 37: Aksoy, using the data from August 1993 to July 1995 obtained from the Turkish State Meterological Service, developed a quadratic relationship between (H/H_o) and (n/N) in order to estimate monthly average global radiation for Ankara, Antalya, Samsun, Konya, Urfa and Izmir, Turkey, as follows [40]:

$$\frac{H}{H_o} = 0.148 + 0.668\left(\frac{S}{S_o}\right) - 0.079\left(\frac{S}{S_o}\right)^2 \tag{43}$$

Model 38: Tiris and Tiris derived the following equations from the experimental data measured in Gebze, Turkey in the period from January 1984 to December 1992 [41].

$$\frac{H_d}{H} = 0.652 - 0.482\left(\frac{S}{S_o}\right) \quad \text{for } 0.23 < \left(\frac{S}{S_o}\right) < 0.76 \tag{44}$$

Model 39: Said et al. obtained the following equations to estimate monthly average global and diffuse radiation on a horizontal surface at Tripoli, Libya [42]:

$$\frac{H}{H_o} = 0.215 + 0.527\left(\frac{S}{S_o}\right) \tag{45a}$$

$$\frac{H}{H_o} = 0.1 + 0.874\left(\frac{S}{S_o}\right) - 0.255\left(\frac{S}{S_o}\right)^2 \tag{45b}$$

$$\frac{H_d}{H} = 1.625 - 3.421\left(\frac{S}{S_o}\right) + 2.185\left(\frac{S}{S_o}\right)^2 \tag{45c}$$

Model 40: Ampratwum and Dorvlo suggested the following logarithmic equation for Seeb weather station in Oman [43]:

$$\frac{H}{H_o} = 0.6376 + 0.2490\log\left(\frac{S}{S_o}\right) \tag{46}$$

Model 41: Togrul and Onat developed equations to estimate the monthly mean global solar radiation (H) for Elazig, Turkey [44]:

$$H = -1.3876 + 0.518H_o + 2.3064\left(\frac{S}{S_o}\right) \tag{47a}$$

$$H = 2.765 + 4.9597\sin(\delta) + 2.2984\left(\frac{S}{S_o}\right) \tag{47b}$$

Model 42: Ulgen and Ozbalta proposed the following linear and second degree equations for Izmir-Bornova, Turkey [45]:

$$\frac{H}{H_o} = 0.2424 + 0.5014\left(\frac{S}{S_o}\right) \tag{48a}$$

$$\frac{H}{H_o} = 0.0959 + 0.9958\left(\frac{S}{S_o}\right) - 0.3922\left(\frac{S}{S_o}\right)^2 \tag{48b}$$

Model 43: Ertekin and Yaldiz have suggested following polynomial correlation equations for Antalya city of Turkey [46]:

$$\frac{H}{H_o} = -2.4275 + 11.946\left(\frac{S}{S_o}\right) - 16.745\left(\frac{S}{S_o}\right)^2 + 7.9575\left(\frac{S}{S_o}\right)^3 \tag{49}$$

Model 44: Elagib and Mansell have investigated the possibility of establishing monthly-specific equations for estimating global solar radiation across Sudan. The authors have reported to the best performing equations for each month as given following [47]:

$$\frac{H}{H_o} = 0.1357 + 0.3204(\varphi) + 0.0422(Z) + 0.4947\left(\frac{S}{S_o}\right) \quad \text{for January} \tag{50a}$$

$$\frac{H}{H_o} = 0.1563 + 0.3166(\varphi) + 0.1006(Z) + 0.4593\left(\frac{S}{S_o}\right) \quad \text{for February} \tag{50b}$$

$$\frac{H}{H_o} = 0.7727\left(\frac{S}{S_o}\right)^{0.7263} \quad \text{for March} \tag{50c}$$

$$\frac{H}{H_o} = 0.1640 + 0.0397(Z) + 0.5773\left(\frac{S}{S_o}\right) \quad \text{for April} \tag{50d}$$

$$\frac{H}{H_o} = 0.0709 + 0.8967\left(\frac{S}{S_o}\right) - 0.2258\left(\frac{S}{S_o}\right)^2 \quad \text{for May} \tag{50e}$$

$$\frac{H}{H_o} = -0.0348 + 1.5078\left(\frac{S}{S_o}\right) - 0.8246\left(\frac{S}{S_o}\right)^2 \quad \text{for June} \tag{50f}$$

$$\frac{H}{H_o} = 0.3205 + 0.1444(\varphi) + 0.0782(h) + 0.2916\left(\frac{S}{S_o}\right) \quad \text{for July} \tag{50g}$$

$$\frac{H}{H_o} = 0.2720 + 0.0369(\varphi) + 0.1017(Z) + 0.3888\left(\frac{S}{S_o}\right) \quad \text{for August} \tag{50h}$$

$$\frac{H}{H_o} = -0.3710 + 2.5783\left(\frac{S}{S_o}\right) - 1.6788\left(\frac{S}{S_o}\right)^2 \quad \text{for September} \tag{50i}$$

$$\frac{H}{H_o} = 0.1593 - 0.1043(\varphi) + 0.0609(Z) + 0.5916\left(\frac{S}{S_o}\right) \quad \text{for October} \tag{50j}$$

$$\frac{H}{H_o} = 0.1786 + 0.0199(Z) + 0.5441\left(\frac{S}{S_o}\right) \quad \text{for November} \tag{50k}$$

$$\frac{H}{H_o} = 0.1714 + 0.1329(\varphi) + 0.0482(Z) + 0.5015\left(\frac{S}{S_o}\right) \quad \text{for December} \tag{50l}$$

Model 45: Chegaar and Chibani have suggested two models for estimating monthly average daily global on a horizontal surface [48]:

$$\frac{H}{H_o} = 0.309 + 0.368\left(\frac{S}{S_o}\right) \quad \text{for Algiers and Oran} \tag{51a}$$

$$\frac{H}{H_o} = 0.367 + 0.367\left(\frac{S}{S_o}\right) \quad \text{for Beni Abbas} \tag{51b}$$

$$\frac{H}{H_o} = 0.233 + 0.591\left(\frac{S}{S_o}\right) \quad \text{for Tamanrasset} \tag{51c}$$

Model 46: Ulgen and Hepbasli developed the following empirical correlations for the city of Izmir, Turkey, for estimating H [49].

$$\frac{H}{H_o} = 0.3092\cos(\varphi) + 0.4931\left(\frac{S}{S_o}\right) \tag{52a}$$

$$\frac{H}{H_o} = 0.2408 + 0.3625\left(\frac{S}{S_o}\right) + 0.4597\left(\frac{S}{S_o}\right)^2 - 0.3708\left(\frac{S}{S_o}\right)^3 \tag{52b}$$

Model 47: Togrul and Togrul suggested the following equations which they obtained from the relation between S/S_o and H/H_o by trying different regression types for Ankara, Antalya, Izmir, Yenihisar (Aydın), Yumurtalık (Adana) and Elazıg in Turkey [50]:

$$\frac{H}{H_o} = 0.318 + 0.449\left(\frac{S}{S_o}\right) \tag{53a}$$

$$\frac{H}{H_o} = 0.698 + 0.2022\ln\left(\frac{S}{S_o}\right) \tag{53b}$$

$$\frac{H}{H_o} = 0.1541 + 1.1714\left(\frac{S}{S_o}\right) - 0.705\left(\frac{S}{S_o}\right)^2 \tag{53c}$$

$$\frac{H}{H_o} = 0.1796 + 0.9813\left(\frac{S}{S_o}\right) - 0.2958\left(\frac{S}{S_o}\right)^2 - 0.2657\left(\frac{S}{S_o}\right)^3 \tag{53d}$$

$$\frac{H}{H_o} = 0.3396\, e^{0.8985(S/S_o)} \tag{53e}$$

$$\frac{H}{H_o} = 0.7316\left(\frac{S}{S_o}\right)^{0.4146} \tag{53f}$$

Model 48: Akpabio and Etuk suggested an Angström-type correlation equation given as following by using measurements of global solar radiation and sunshine duration data during the period from 1984 to 1999 at Onne (within the rainforest climatic zone of southern Nigeria) [51]:

$$\frac{H}{H_o} = 0.23 + 0.38\left(\frac{S}{S_o}\right) \tag{54}$$

Model 49: Ulgen and Hepbasli suggested the following the linear and third order polynomial equations for Ankara, Istanbul and Izmir in Turkey [52]:

$$\frac{H}{H_o} = 0.2671 + 0.4754\left(\frac{S}{S_o}\right) \tag{55a}$$

$$\frac{H}{H_o} = 0.2854 + 0.2591\left(\frac{S}{S_o}\right) + 0.6171\left(\frac{S}{S_o}\right)^2 - 0.4834\left(\frac{S}{S_o}\right)^3 \tag{55b}$$

Model 50: Almorox and Hontoria proposed the following exponential equation [53]:

$$\frac{H}{H_o} = -0.0271 + 0.3096\exp\left(\frac{S}{S_o}\right) \tag{56}$$

Model 51: Ahmad and Ulfat have suggested to first and second order polynomial equations developed for Karachi of Pakistan. These equations are given as following, respectively [54]:

$$\frac{H}{H_o} = 0.324 + 0.405\left(\frac{S}{S_o}\right) \tag{57a}$$

$$\frac{H}{H_o} = 0.348 + 0.320\left(\frac{S}{S_o}\right) + 0.070\left(\frac{S}{S_o}\right)^2 \tag{57b}$$

Model 52: Rensheng et al. suggested a logarithmic relationship between the daily global radiation/daily extraterrestrial solar radiation (H/H_o) and the temperature difference between the maximum and minimum daily air temperature ($T_M - T_m$) as equations given following [55]:

$$\frac{H}{H_o} = a\ln(T_M - T_m) + b\left(\frac{S}{S_o}\right)^c + d \tag{58}$$

where a, b, c and d were empirical coefficients which they gave their study [61].

Model 53: Almorox et al. reported the monthly-specific equations for estimating global solar radiation from sunshine hours for Toledo, Spain as given following [56]:

$$\frac{H}{H_o} = 0.285 + 0.444\left(\frac{S}{S_o}\right) \quad \text{for January,} \tag{59a}$$

$$\frac{H}{H_o} = 0.272 + 0.465\left(\frac{S}{S_o}\right) \quad \text{for February} \tag{59b}$$

$$\frac{H}{H_o} = 0.291 + 0.491\left(\frac{S}{S_o}\right) \quad \text{for March} \tag{59c}$$

$$\frac{H}{H_o} = 0.266 + 0.495\left(\frac{S}{S_o}\right) \quad \text{for April} \tag{59d}$$

$$\frac{H}{H_o} = 0.286 + 0.475\left(\frac{S}{S_o}\right) \quad \text{for May} \tag{59e}$$

$$\frac{H}{H_o} = 0.311 + 0.439\left(\frac{S}{S_o}\right) \quad \text{for June} \tag{59f}$$

$$\frac{H}{H_o} = 0.329 + 0.406\left(\frac{S}{S_o}\right) \quad \text{for July} \tag{59g}$$

$$\frac{H}{H_o} = 0.313 + 0.410\left(\frac{S}{S_o}\right) \quad \text{for August} \tag{59h}$$

$$\frac{H}{H_o} = 0.271 + 0.479\left(\frac{S}{S_o}\right) \quad \text{for September} \tag{59i}$$

$$\frac{H}{H_o} = 0.259 + 0.465\left(\frac{S}{S_o}\right) \quad \text{for October} \tag{59j}$$

$$\frac{H}{H_o} = 0.279 + 0.431\left(\frac{S}{S_o}\right) \quad \text{for November} \tag{59k}$$

$$\frac{H}{H_o} = 0.282 + 0.428\left(\frac{S}{S_o}\right) \quad \text{for December} \tag{59l}$$

Model 54: Tahran and Sarı have suggested two models to predict solar radiation over the Central Black Sea Region of Turkey. These quadratic and cubic polynomial models are given as following, respectively [57]:

$$\frac{H}{H_o} = 0.1874 + 0.8592\left(\frac{S}{S_o}\right) - 0.4764\left(\frac{S}{S_o}\right)^2 \tag{60a}$$

$$\frac{H}{H_o} = 0.1520 + 1.1334\left(\frac{S}{S_o}\right) - 1.1126\left(\frac{S}{S_o}\right)^2 + 0.4516\left(\frac{S}{S_o}\right)^3 \tag{60b}$$

Model 55: Jin et al. have suggested, based on the radiation data and the geographical information including latitude and altitude at all 69 stations in China, nine general equations are given as following [58]:

$$\frac{H}{H_o} = 0.1332 + 0.6471\left(\frac{S}{S_o}\right) \tag{61a}$$

$$\frac{H}{H_o} = 0.1404 + 0.6126\left(\frac{S}{S_o}\right) + 0.0351\left(\frac{S}{S_o}\right)^2 \tag{61b}$$

$$\frac{H}{H_o} = 0.1275 + 0.7251\left(\frac{S}{S_o}\right) - 0.2299\left(\frac{S}{S_o}\right)^2 + 0.1837\left(\frac{S}{S_o}\right)^3 \tag{61c}$$

$$\frac{H}{H_o} = 0.0855 + 0.0020(\varphi) + 0.030Z + 0.5654\left(\frac{S}{S_o}\right) \tag{61d}$$

$$\frac{H}{H_o} = 2.1186 - 2.0014\cos(\varphi) + 0.0304Z + 0.5622\left(\frac{S}{S_o}\right) \tag{61e}$$

$$\frac{H}{H_o} = (0.1094 + 0.0014(\varphi) + 0.0212Z) + (0.5176 + 0.0012(\varphi) + 0.0150Z)\left(\frac{S}{S_o}\right) \tag{61f}$$

$$\frac{H}{H_o} = (1.8790 - 1.7516\cos(\varphi) + 0.0205Z) + (1.0819 - 0.5409\cos(\varphi) + 0.0169Z)\left(\frac{S}{S_o}\right) \tag{61g}$$

$$\frac{H}{H_o} = (0.0218 + 0.0033(\varphi) + 0.0443Z) + (0.9979 - 0.0092(\varphi) - 0.0852Z)\left(\frac{S}{S_o}\right) + (-0.5579 + 0.0120(\varphi) + 0.1005Z)\left(\frac{S}{S_o}\right)^2 \tag{61h}$$

$$\frac{H}{H_o} = (4.2510 - 4.1878\cos(\varphi) + 0.0437Z) + (-10.5774 + 11.4512\cos(\varphi) - 0.0832Z)\left(\frac{S}{S_o}\right) + (12.7247 - 13.0994\cos(\varphi) + 0.1000Z)\left(\frac{S}{S_o}\right)^2 \tag{61i}$$

where H is the monthly average daily global radiation, H_o is the monthly average daily extraterrestrial radiation, S is the actual sunshine duration, S_o is the maximum possible sunshine duration, φ is the latitude of the site, Z is the altitude of the site in kilometers.

Model 56: Aras et al. have suggested following linear and polynomial correlation equations to use generally for twelve provinces in the Central Anatolia Region of Turkey [59]:

$$\frac{H}{H_o} = 0.3078 + 0.4166\left(\frac{S}{S_o}\right) \tag{62a}$$

$$\frac{H}{H_o} = 0.3398 + 0.2868\left(\frac{S}{S_o}\right) + 0.1187\left(\frac{S}{S_o}\right)^2 \tag{62b}$$

$$\frac{H}{H_o} = 0.4832 - 0.6161\left(\frac{S}{S_o}\right) + 1.8932\left(\frac{S}{S_o}\right)^2 - 1.0975\left(\frac{S}{S_o}\right)^3 \tag{62c}$$

Model 57: Rensheng et al. have suggested new equations, basing on the Angström model and the Bahel model, by using the daily global radiation data and sunshine hours from 1994 to 1998 at 86 stations in China. These equations are given as following [60]:

$$\frac{H}{H_o} = 0.176 + 0.563\left(\frac{S}{S_o}\right) \tag{63a}$$

$$\frac{H}{H_o} = (0.122 + 0.001(\varphi) + 2.57\times10^{-2}Z) + 0.543\left(\frac{S}{S_o}\right) \tag{63b}$$

$$\frac{H}{H_o} = (0.280 - 0.141\cos(\varphi) + 2.60\times10^{-2}Z) + 0.542\left(\frac{S}{S_o}\right) \tag{63c}$$

$$\frac{H}{H_o} = (0.275 + 4.27\times10^{-5}\lambda - 0.141\cos(\varphi) + 2.63\times10^{-2}Z) + 0.542\left(\frac{S}{S_o}\right) \tag{63d}$$

$$\frac{H}{H_o} = (0.117 + 4.11\times10^{-5}\lambda - 0.001\varphi + 2.59\times10^{-2}Z) + 0.543\left(\frac{S}{S_o}\right) \tag{63e}$$

$$\frac{H}{H_o} = [-0.196\cos(\varphi) + 2.2\times10^{-2}Z + 0.329] + [0.097\cos(\varphi) + 6.72\times10^{-3}Z + 0.457]\left(\frac{S}{S_o}\right) \tag{63f}$$

$$\frac{H}{H_o} = [0.0001\lambda - 0.195\cos(\varphi) + 2.28\times10^{-2}Z + 0.313] + [-0.0002\lambda + 0.097\cos(\varphi) + 5.69\times10^{-3}Z + 0.476]\left(\frac{S}{S_o}\right) \tag{63g}$$

$$\frac{H}{H_o} = [0.0001\lambda + 0.002\varphi + 2.27\times10^{-2}Z + 0.094] + [-0.0002\lambda - 0.0008\varphi + 5.36\times10^{-3}Z + 0.586]\left(\frac{S}{S_o}\right) \tag{63h}$$

$$\frac{H}{H_o} = 0.150 + 1.145\left(\frac{S}{S_o}\right) - 1.474\left(\frac{S}{S_o}\right)^2 + 0.963\left(\frac{S}{S_o}\right)^3 \tag{63i}$$

$$\frac{H}{H_o} = (0.001\varphi + 2.41\times10^{-2}Z + 0.109) + 1.029\left(\frac{S}{S_o}\right) - 1.216\left(\frac{S}{S_o}\right)^2 + 0.787\left(\frac{S}{S_o}\right)^3 \tag{63j}$$

$$\frac{H}{H_o} = [-0.112\cos(\varphi) + 2.43\times10^{-2}Z + 0.234] + 1.026\left(\frac{S}{S_o}\right) - 1.209\left(\frac{S}{S_o}\right)^2 + 0.782\left(\frac{S}{S_o}\right)^3 \tag{63k}$$

$$\frac{H}{H_o} = (0.0007\varphi + 2.44\times10^{-2}Z - 0.005\lambda + 2.24\times10^{-5}\lambda^2 + 0.370) + 1.026\left(\frac{S}{S_o}\right) - 1.208\left(\frac{S}{S_o}\right)^2 + 0.783\left(\frac{S}{S_o}\right)^3 \tag{63l}$$

$$\frac{H}{H_o} = [-0.087\cos(\varphi) + 2.44\times10^{-2}Z - 0.004\lambda + 1.86\times10^{-5}\lambda^2 + 0.426] + 1.024\left(\frac{S}{S_o}\right) - 1.204\left(\frac{S}{S_o}\right)^2 + 0.779\left(\frac{S}{S_o}\right)^3 \tag{63m}$$

$$\frac{H}{H_o} = [-0.233\cos(\varphi) + 2.64\times10^{-2}Z + 0.336] + [2.140\cos(\varphi) - 0.1Z - 0.670]\left(\frac{S}{S_o}\right) + [-5\cos(\varphi) + 0.3Z + 2.744]\left(\frac{S}{S_o}\right)^2 + [3.042\cos(\varphi) - 0.2Z - 1.638]\left(\frac{S}{S_o}\right)^3 \quad (63n)$$

$$\frac{H}{H_o} = [-0.141\cos(\varphi) + 2.84\times10^{-2}Z - 0.014\lambda + 6.7\times10^{-5}\lambda^2 + 1.012] + [1.740\cos(\varphi) - 0.1Z + 0.069\lambda - 0.003\lambda^2 - 4.061]\left(\frac{S}{S_o}\right) + [-3.867\cos(\varphi) + 0.3Z - 0.199\lambda + 0.0009\lambda^2 + 12.402]\left(\frac{S}{S_o}\right)^2 + [2.115\cos(\varphi) - 0.2Z + 0.164\lambda - 0.0008\lambda^2 - 9.442]\left(\frac{S}{S_o}\right)^3 \quad (63o)$$

where λ, φ and Z (in kilometers) are the longitude, latitude and altitude of the used stations.

Model 58: Bakirci has suggested following polynomial correlation equations for Erzurum city of Turkey [61]:

$$\frac{H}{H_o} = 0.6307 - 0.7251\left(\frac{S}{S_o}\right) + 1.2089\left(\frac{S}{S_o}\right)^2 - 0.4633\left(\frac{S}{S_o}\right)^3 \quad (64)$$

Model 59: Bakirci reported equations for estimating global solar radiation from sunshine hours for Erzurum, Turkey as follows [62]:

$$\frac{H_c}{H_o} = 0.6716 + 0.0760\left(\frac{S}{S_o}\right) \quad (65a)$$

$$\frac{H_c}{H_o} = 0.5622 + 0.5444\left(\frac{S}{S_o}\right) - 0.4490\left(\frac{S}{S_o}\right)^2 \quad (65b)$$

Model 60: Bakirci reported the original Angström-type equations including the linear, second-order and fifth-order polynomial relationships between the monthly average values of (H/H_c) and (S/S_o) as follows [63]:

$$\frac{H}{H_c} = 0.7836 - 0.0460\left(\frac{S}{S_o}\right) \quad (66a)$$

$$\frac{H}{H_c} = 1.0192 - 1.0547\left(\frac{S}{S_o}\right) + 0.9661\left(\frac{S}{S_o}\right)^2 \quad (66b)$$

$$\frac{H}{H_c} = -11.225 + 128.010\left(\frac{S}{S_o}\right) - 516.900\left(\frac{S}{S_o}\right)^2 + 994.730\left(\frac{S}{S_o}\right)^3 - 920.350\left(\frac{S}{S_o}\right)^4 + 329.93\left(\frac{S}{S_o}\right)^5 \quad (66c)$$

3. Results and discussion

In this study, the regression constants have been generally computed using observations of sunshine hours and monthly average daily global radiation in given a location. In the studies carried out in this field by many authors, the models used to estimate the monthly average daily global solar radiation on a horizontal surface can be categorized in four groups, as seen from Eqs. (6) to (66). These groups consist of the relations derived from the Angström-type equations and, the types of the models are given as follows:

Group I (linear models): The models derived from the Angström-type regression equation was called the linear models because the empirical coefficients *a* and *b* were obtained from the results of the first order regression analysis (such as Model 2, 8, 13 and 16). (ii) *Group II (polynomial models)*: Some researcher suggested that the modified Angström type relation is a second, three and bigger order polynomial equation to estimate the monthly average daily global radiation on a horizontal surface (such as Model 28, 30, 54 and 60). (iii) *Group III (angular models)*: There are the angular models derived by modifying the original Angström-type equation (such as Model 1, 6, 9 and 19). (iv) *Group IV (other models)*: Special cases of the modified Angström-type equation were categorized in this group. These cases include a logarithmic term, non-linear model and exponential equation (such as Model 47, 52, 55 and 57).

4. Conclusion

Solar radiation data are essential in the design and study of solar energy conservation devices. In this regard, empirical correlations are developed to estimate the monthly average daily global radiation on a horizontal surface. Sunshine based models are employed for estimation global solar radiation for a location. The correlation equations given in this study will enable the solar energy researcher to use the estimated data with trust because of its fine agreement with the observed data.

The following conclusions may be drawn from the present study:

(1) Solar energy technologies offer a clean, renewable and domestic energy source, and are essential components of a sustainable energy future. In the design and evaluation of solar energy, information on solar radiation and its components at a given location is needed. In this regard, solar radiation models are of big importance.
(2) Most of solar radiation models given to estimate the monthly average daily global solar radiation are of the modified Angström-type equation.
(3) It may be concluded that the models presented in this study may be used reasonably well for estimating the solar radiation at a given location and possibly in elsewhere with similar climatic conditions.

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